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SOME DEFENCE APPLICATIONS OF
SUPERCONDUCTORS

by

Arthur W. Johnson

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Chemical Sources Section
Energy Conversion Division

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ABSTRACT

Two basic applications of superconductivity are described. The first involves the use of Type II superconductors in magnets, motors and generators to improve efficiency and reduce weight and volume. The second relates to the use of superconducting junctions in magnetometers and gradio-meters to provide instruments with very high sensitivity. Possible defence use of superconducting materials in these areas is outlined. A brief review of superconductors and their properties is also given.

RÉSUMÉ

Deux applications de base de la supraconductivité sont décrites dans ce rapport. La première comprend l'usage des supraconducteurs de la seconde espèce dans des aimants, des moteurs et des générateurs afin d'améliorer leur efficacité et de réduire leur poids et volume. La deuxième application traite des jonctions supraconductrices employées dans des magnétomètres et gradientmètres ultrasensibles. L'emploi possible de ces matériaux pour la défense est décrit sommairement. Une brève revue des supraconducteurs et de leurs propriétés est aussi présentée.

(iii)

INTRODUCTION

Superconductors are materials possessing the ability to conduct electrical currents with almost zero power loss when cooled below some critical transition temperature, T_c, a temperature which is unique for each material. The residual resistance of such conductors has been reported to be $< 4 \times 10^{-25}$ ohm-m (1) compared to 2×10^{-8} ohm-m for copper at 20°C. There is thus an advantage of $\sim 10^{17}$ in reduced resistivity in using these materials at low temperature in the superconducting state compared to normal, resistive conductors at room temperature. For some metallic compounds $T_c \sim 20$ K, but for pure metals $0 < T_c \leq 16$K; in many pure metals $T_c < 2$ K. A number of elements, such as Ag, Au, Cu, Fe, Pt, etc. do not exhibit the property of superconductivity, but when they are combined with certain other metals, the resultant alloys are superconducting, occasionally with a T_c higher than that of the individual components; e.g. Au_3Te_5, CuGe. On a practical scale, there are only a few superconductors with the desirable characteristics of relatively high T_c, high current-carrying capacity in high magnetic fields and ease of fabrication.

The vanishingly small resistance of superconductors has been successfully exploited in superconductive magnets in which current densities orders of magnitude higher than in conventional windings have been achieved. The resultant high magnetic fields are useful in superconductive motors and generators and in solenoids for electrical energy storage and MHD electrical power generators.

The quantum nature of superconductive tunnelling in Josephson junctions has led to the development of magnetometers and gradiometers with sensitivities limited only by thermal noise. These devices are especially useful in magnetic anomaly detection and in ultra-sensitive voltmeters.

In this report some of the possible defence applications of superconducting materials are reviewed.

BACKGROUND

Superconductivity was first discovered by Kamerlingh Onnes in 1911 while measuring the electrical resistance of mercury at low temperature. He also found that superconducting mercury reverted to the normal or resistive state in a relatively weak magnetic field or when carrying a current corresponding

to such a field. All of the early superconductors displayed this behaviour
and it was shown that they were also perfectly diamagnetic. When cooled below
T_c in the presence of a magnetic field, they expelled the magnetic flux until
the field exceeded some critical value, H_c, at which point they became normal.
The H_c exhibited by these Type I superconductors is too low for these materials
to have any technological value in producing magnetic fields. Typically
$H_c < 0.1$ Tesla (1 T = 10,000 Oersted), which is far below the field of 2 T
attainable with iron-core electromagnets.

Type II superconductors, on the other hand, possess an additional
magnetic state which allows them to be operated in a high magnetic field. At
low fields, they behave like Type I superconductors and are diamagnetic until
the first critical field point, H_{c1} is attained. As the field is increased,
they pass to a mixed state in which the applied field enters the material in
the form of fluxoids consisting of cylindrical bundles of flux surrounded by
vortices of supercurrents. Each fluxoid contains one quantum of flux. In
materials containing strong pinning or anchoring centres for these fluxoids,
such as lattice irregularities or grain boundaries, their motion is constrained
and there is no flow of flux or dissipation of energy. When operated in this
region, some materials can support very high current densities and can generate
very high magnetic fields. If, however, the field exceeds H_{c2}, the upper limit
of the mixed state, the superconductor will become normal, i.e. resistive.
In pure, undamaged Type II superconductors a third state may exist above H_{c2} and
limited by H_{c3}. This state is characterized by a superconducting surface layer or
sheath surrounding a normal core. It is analogous to supercooling in a liquid
and appears to have no practical value in extending the high field region.

The characteristic critical magnetic field rating of a super-
conductor decreases with increasing temperature and values for different
materials are usually quoted at a common temperature, typically 4.2 K. T_c
is also inversely proportional to magnetic field and is quoted for zero field.
A third parameter, current density, J, is similarly dependent upon T and H
and is usually listed for 4.2 K and a given magnetic field. This interdepen-
dence of variables is shown in Figure 1. The J_c-T_c-H_c surface in such a
diagram represents the upper limit of possible operation of the superconductor.
The actual operating point lies somewhat below this surface to allow for a
margin of security.

Of the more than one thousand superconductors presently known,
most are Type II, but only a few have technological promise. Some of these
are listed in Table I (2). It can be seen that all have $H_{c2} \geq 11$ T which is
more than 100 times higher than the H_c for Type I superconductors. The
materials which have been used in commercial applications include Nb-Zr,
Nb-Ti, Nb_3Sn and V_3Ga. The first two are ductile alloys from which wires can
be made following conventional drawing procedures. Nb-Zr has a slightly
higher T_c than Nb-Ti, but the higher critical field and greater ductility of
Nb-Ti together with its relatively low cost have led to its preferred use in
producing magnetic fields up to 8 T at 4.2 K, the boiling point of liquid
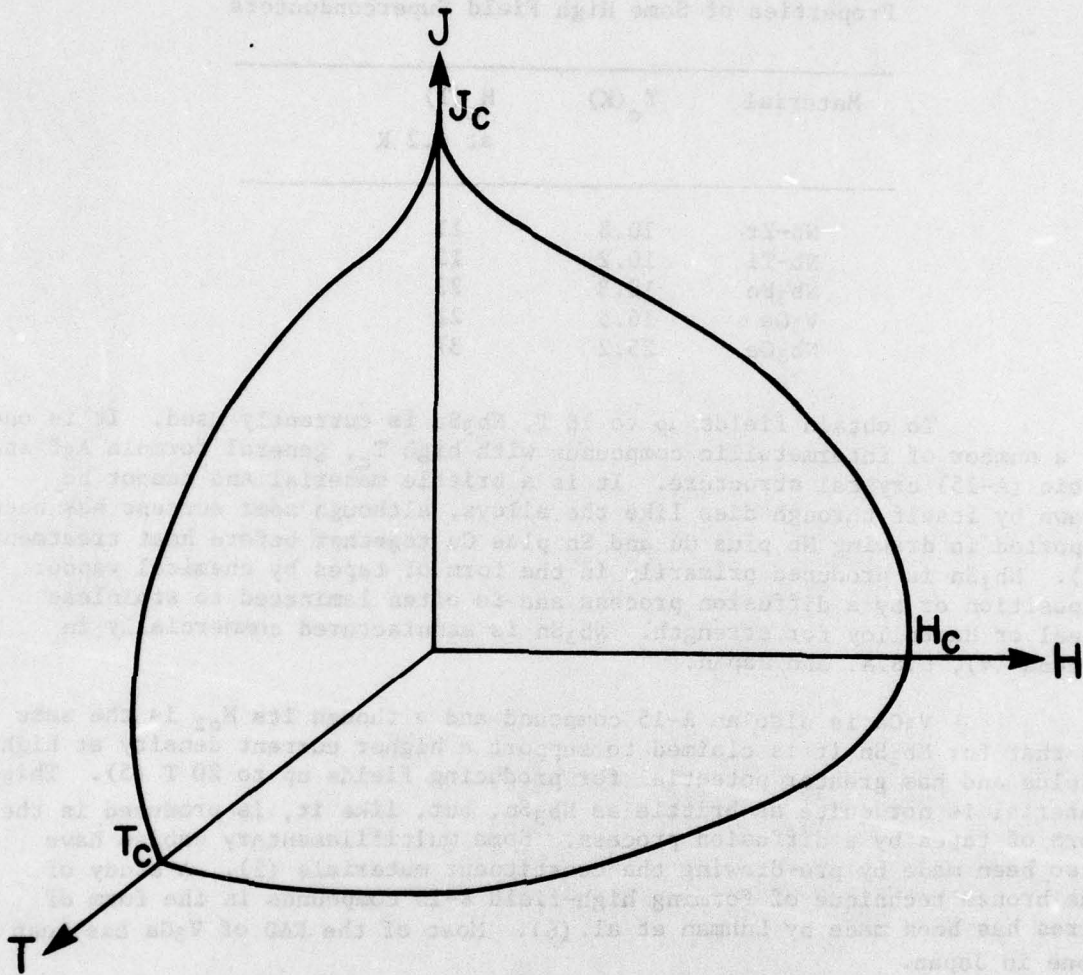helium.

FIGURE 1. *Current-Field-Temperature Characteristics of Type II Superconductors*

TABLE 1

Properties of Some High Field Superconductors

Material	T_c (K)	H_c (T) at 4.2 K
Nb-Zr	10.8	11
Nb-Ti	10.2	12
Nb_3Sn	18.3	22
V_3Ga	16.5	22
Nb_3Ge	23.2	37

To obtain fields up to 16 T, Nb_3Sn is currently used. It is one of a number of intermetallic compounds with high T_c, general formula A_3B and cubic (A-15) crystal structure. It is a brittle material and cannot be drawn by itself through dies like the alloys, although some success has been reported in drawing Nb plus Cu and Sn plus Cu together before heat treatment (3). Nb_3Sn is produced primarily in the form of tapes by chemical vapour deposition or by a diffusion process and is often laminated to stainless steel or Hastelloy for strength. Nb_3Sn is manufactured commercially in Canada (4), U.S.A. and Japan.

V_3Ga is also an A-15 compound and although its H_{c2} is the same as that for Nb_3Sn it is claimed to support a higher current density at high fields and has greater potential for producing fields up to 20 T (5). This material is not quite as brittle as Nb_3Sn, but, like it, is produced in the form of tapes by a diffusion process. Some multifilamentary cables have also been made by pre-drawing the constituent materials (5). A study of the bronze technique of forming high-field A-15 compounds in the form of wires has been made by Luhman et al. (6). Most of the R&D of V_3Ga has been done in Japan.

The superconductor with the highest transition temperature known to date, $T_c = 23.2$ K, is Nb_3Ge, and although this temperature is above 20.3 K, the boiling point of liquid hydrogen, and the material is therefore attractive from the point of view of refrigeration requirements, the attainable field at this temperature is less than 10 T. It must be used in liquid helium or helium vapour to achieve the high fields of which it is capable. The current density and the magnetic field attainable are ultimately higher than for Nb-Ti, Nb_3Sn and V_3Ga (7) and the material has great promise although it is not yet available commercially.

Type II superconductors are sometimes called "hard" super-conductors because of their physical characteristics in comparison with the "soft" Type I metals, e.g. Pb, Sn, In, Hg, etc.

Superconductors used for generating magnetic fields are not employed alone but are clad in a normal conductor such as Cu or Al to provide a degree of cryogenic stability. In the absence of such stabilization, local sections of the current-carrying superconductor may become normal due to flux jumping as the field is increased and the heat generated in this resistive section would rapidly propagate leading to quenching of the field. The resistance of the surrounding copper is much lower than that of the superconductive material in the normal state and the copper can support the current while dissipating the heat to the refrigerant. As soon as the local temperature falls below T_c, the superconductor resumes the load.

Further stability is obtained by reducing the diameter of the superconductor to micron-size filaments embedded in a copper matrix; flux jumping and hysteresis effects are thereby minimized. Twisting the filaments reduces inductive currents when the field changes, and eddy current losses in pulsed or AC applications are minimized when each filament in its copper sheath is surrounded by a more resistive material such as cupro-nickel. Finally, a more even current distribution is obtained when the positions of the twisted filaments in the matrix are transposed relative to each other along the length of the cable. The effect of twisting, but not transposition, may be obtained in diffused or deposited superconductors by suitable etching.

It is not uncommon to have many thousands of filaments in a single conductor. The actual number used and the overall dimensions of the wire are determined by the ultimate use of the superconductor. Figure 2 is a cross-section of a 1.67 mm x 3.35 mm composite conductor capable of carrying 2200 A and containing 2133 strands of Nb-Ti in a copper matrix.

APPLICATIONS

MAGNETS

INTRODUCTION

Conventional magnets are limited to fields of about 2 T because of saturation of the iron core. The iron in the magnetic circuit concentrates the flux; if it were removed to eliminate the saturation limitation, the electrical power needed to generate the same field would rise by a factor of about 10^3(8) resulting in enormous power losses and corresponding cooling problems. Some high-field, water-cooled magnets have been built but they are bulky and the operational costs are high.
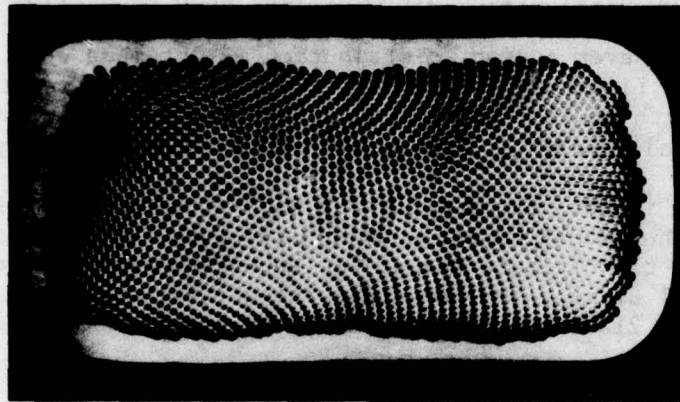
FIGURE 2.   Cross-section of Nb-Ti Multi-filamentary Superconductor
(Magnetic Corporation of America)

Superconducting magnets are compact and light-weight in comparison with conventional magnets and their operational costs are low. Most of the volume is occupied by the winding which is dissipationless and can support the current density needed to generate high magnetic fields without iron. A 16 T solenoid wound with Nb_3Sn tape, for example, has been described which operates at 130 A and at an average current density of 1.55×10^4 Acm^{-2} (9) and a 17.5 T mixed conductor solenoid is reported to have a power consumption of less than 2 kW for energization (12). This may be compared with a power dissipation of 4.75 MW in an 18 T water-cooled solenoid with smaller bore (10). In 2 T electro-magnets, the current density is of the order of 150 Acm^{-2} (8). The cooling requirements for the resistive solenoid amount to many thousands of gallons of water per second whereas the 17.5 T superconducting solenoid consumes 4 ℓ of liquid helium per hour.

Superconducting magnets do not usually achieve their designed field strength when first energized but gradually approach this rating after a number of quenches. This phenomenon is known as "training" of the magnet and has been ascribed to strain on the winding (11). Strong forces exist in the winding of an operating magnet and if the supporting structure is not sufficiently rigid, movement of the conductor leads to strain and possible premature quenching. In some cases the magnet may never achieve its designed strength. Vacuum potting with epoxy resin, pre-stressed aluminium reinforcement and axially-layered windings are among the methods employed to improve rigidity and reduce training. The layered or stacked pancake technique is used with tapes and is particularly useful in trimming the field to achieve the desired uniformity when necessary. The strongest superconductive magnet built to date is constructed in this manner. It consists of two independent co-axial solenoids; the outer coil is wound with Nb_3Sn tape and the inner coil with V_3Ga. Together they produce a field of 17.5 T in a clear bore of 3.1 cm. The magnet weighs 349 kg and measures 45 cm in diameter and 62 cm long (12).

INDUCTIVE ENERGY STORAGE

The high current-carrying capacity and negligible resistance of Type II superconductors in a high magnetic field offer the possibility of storing large amounts of electrical energy in superconducting solenoids for indefinite periods. The stored energy may be removed continuously or in pulses according to the load presented to the coil. Continuous discharge is of interest to electrical utilities for load levelling and will involve stored energies of $\geq 10^{12}$ J in large underground installations. Of defence interest are smaller, transportable units with pulsed-discharge capability. These units could conceivably be used to drive (airborne) high-power weapon systems. In this application, the solenoid would serve as a power inverter, accepting a low-voltage, slow-pulse DC charge (low average power) and providing a high-voltage, rapid-pulse discharge (high peak power). For airborne single-shot or limited operation, the solenoid could be charged on the ground thereby freeing the system from the additional weight of a dedicated power supply.

A simplified wiring diagram for an inductive energy storage system is shown in Figure 3. Once energized, the solenoid is placed in the persistent mode by allowing the shunt switch to become superconducting. Under these conditions, the electrical current flows in the circuit without loss until the switch is opened. To draw power from the coil, the switch is driven normal by discharging the capacitors through it. Enough energy is dissipated in the switch to exceed its critical current, raise its temperature above T_c and latch it in the open position. Although the persistent switch is in parallel with the solenoid, its resistance when normal is high compared to the load and the power loss is small. Other configurations employing different switching schemes are sometimes used and pulse-forming networks and arc-quenching circuits are incorporated as required. In some cases, power is drawn from the solenoid through coupling to a secondary coil.

The optimum shape for an energy storage coil is the circular solenoid with length/inner diameter $\simeq \frac{1}{2}$ and outer diameter/inner diameter $\simeq 2$ (Brooks coil) (13). This shape provides the maximum inductance for a given length of wire and is desirable since the energy, E, stored in the magnetic field is directly proportional to inductance, L; i.e., $E = \frac{1}{2}LI^2$. Of even greater importance is the dependence of E on the magnetic field intensity which in turn is related to the circulating current. A high-field solenoid with large inductance is thus desirable from the point of view of energy storage; however, on the practical side, coil stresses increase with field strength and coil reinforcement becomes a problem at high fields. Furthermore high inductance can lead to discharge pulses with very high peak voltage, and insulation breakdown within the coil can occur. An additional factor to consider is that if a field external to the solenoid cannot be tolerated, a toroidally-wound coil or segmented torus will be required. This design yields a somewhat lower energy density than the solenoid and is more expensive, but it has the advantage of keeping all of the magnetic field within the winding. The conflicting requirements of field intensity, inductance and shape necessitate a compromise design for a given application.

Inductive energy storage systems employing superconducting coils have an energy density of 10^3-10^4 Jkg^{-1} which is one to two orders of magnitude greater than for long-life capacitors (14). Capacitors may also be slowly charged and quickly discharged in a high energy pulse, but since the energy is stored in the electric field of the capacitor, the voltage of the charging power supply must be the same as the discharge pulse voltage. Capacitors are generally larger and more expensive than superconducting coils of the same energy storage capacity (14).

A number of superconducting coils have been built specifically for pulsed energy storage. The design and development of solenoids with capacities up to 100 kJ to be operated either repetitively or with multiple pulse output from a single charge has been supported by the U.S. Air Force (15). These solenoids were wound with multifilamentary Nb-Ti and could be pulsed to a large fraction of their critical current. Pulses <1 mS long and >10 kV in amplitude were obtained. Coils employing high-field superconductors, such as Nb_3Sn, are under evaluation.

Superconductive Switch

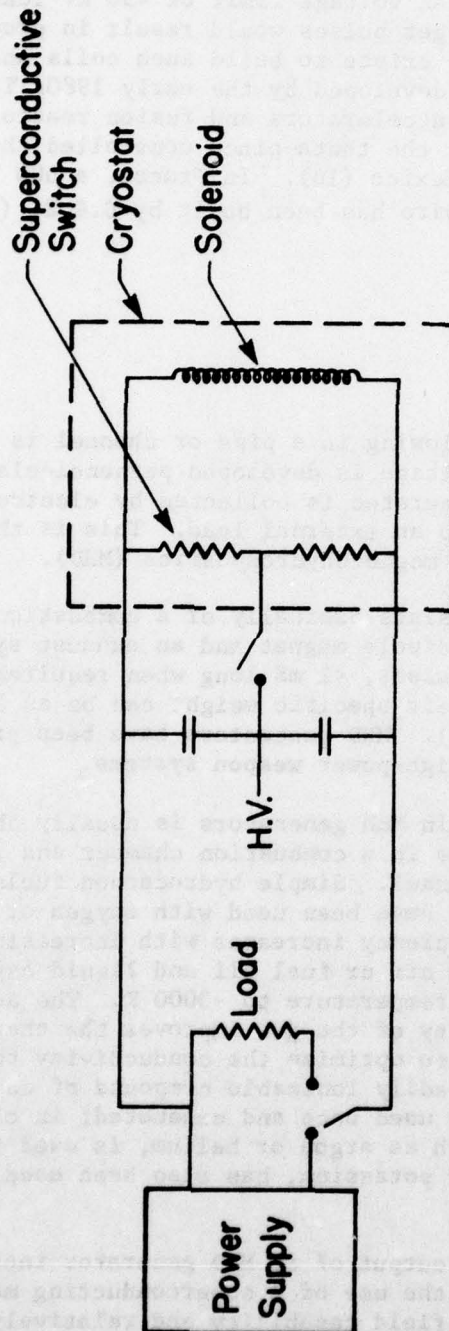Cryostat

Solenoid

H.V.

Load

Power Supply

FIGURE 3. *Simplified Wiring Diagram of a Superconductive Energy Storage System*

        A 100 kJ coil has an electrical capacity of 28 Wh. If all of
this energy were discharged in a 200 µS pulse, the peak power would be 500 MW.
Internal arcing would impose a peak voltage limit of ~50 kV leading to an
operating current of ~10 kA. Longer pulses would result in proportionally
lower peak power. The technology exists to build such coils and larger trans-
portable units could probably be developed by the early 1980s if needed.
Larger fixed systems for nuclear accelerators and fusion reactors have been
built such as the 386 kJ coil for the theta-pinch controlled thermonuclear
test reactor at Los Alamos, New Mexico (16). In France, a 600 kJ coil wound
with aluminium-stabilized Nb-Ti wire has been built by C.G.E. (17).

MHD ELECTRIC POWER GENERATION

        When an ionized gas flowing in a pipe or channel is subjected to
a transverse magnetic field, a voltage is developed perpendicular to the flow
and to the field. The current generated is collected by electrodes placed
in the channel walls and is fed to an external load. This is the principle
of electrical power generation by magnetohydrodynamics (MHD).

        The MHD generator consists basically of a combustion chamber or
a heater for the gas, a channel, dipole magnet and an exhaust system. These
generators can provide megawatt pulses, <1 mS long when required, or they
may be operated continuously. Their specific weight can be as low as 0.2 lb kVA^{-1}
at the tens of megawatt level (15). MHD generators have been proposed as power
supplies for ground or airborne high-power weapon systems.

        The ionized gas used in MHD generators is usually obtained by
burning a fuel at high temperature in a combustion chamber and letting it
expand through a jet into the channel. Simple hydrocarbon fuels such as
natural gas, fuel oil, coal, etc. have been used with oxygen or air as the
oxidizer. Since the burning efficiency increases with increasing temperature,
fuel mixtures such as toluene and air or fuel oil and liquid oxygen have also
been used to raise the operating temperature to ~3000 K. The accompanying
increase in electrical conductivity of the gas improves the thermal-to-electrical
power conversion efficiency, but to optimize the conductivity the gas must
be seeded with about 0.3% of a readily ionizable compound of caesium or potassium.
In open-cycle systems, the gas is used once and exhausted; in closed-cycle
systems, a seeded, noble gas, such as argon or helium, is used repetitively.
A liquid metal, such as sodium or potassium, has also been used in a variation
of the closed-cycle design.

        The electrical power output of an MHD generator increases with the
square of the magnetic field and the use of a superconducting magnet is
advantageous because of its high field capability and relatively light weight.
A number of superconducting MHD magnets have been built in the 4-6 T range
and a light-weight unit was constructed under joint DRB/DIR-USAF sponsorship (18).
Other saddle magnets have been built in the US with USAF funding (15).

The US Air Force has supported development in MHD since 1960 and is concentrating effort in open-cycle combustion systems (15). Most experience in MHD has been obtained on systems designed for central station power generation, especially in U.S.A. and Japan and in U.S.S.R. where a 25 MW system is operating. It is expected that MHD electrical power generation for military applications will be available in the early 1980s when difficulties with coil reinforcement and premature quenching will have been solved.

MOTORS AND GENERATORS

The output of an electric motor or generator of given size is dependent upon the magnetic flux density, the effective linear current density and the rotational speed. In conventional machines, the limitations on the flux and current density are similar to those for electromagnets and may be circumvented in the design by the use of superconductive windings. The elimination of iron in the stator doubles the allowable space for the windings and, with the increase in current density, an improvement in output by a factor of about eight may be obtained (19). Conversely a weight and size advantage may be gained by using a motor with superconductive windings instead of a conventional machine. Efficiency is also improved by the reduction of I^2R losses and, in motors, the torque may be increased in proportion to the increased flux density. These gains, however, only become meaningful in machines larger than about 500 HP due to refrigeration requirements and the complexities of operation at liquid helium temperature.

There are two basic types of DC motor with several possible configurations for each. The most common is the heteropolar machine which employs a wound, rotating armature with commutator and a stationary field winding. Although widely used in conventional machines, this design has a major disadvantage for superconductive motors in that the full reaction of motor loading is transmitted directly to the field. This winding is super- conductive and must be surrounded by a dewar assembly and the relatively massive supporting structure for the winding imposes a high load on the refrigeration system. In addition there are thermal and mechanical problems associated with the armature which have to be overcome. Magnetic material must not be present in the rotor body and electrically non-conducting materials are required to support the windings in order to prevent excessive eddy current losses. Gains in efficiency of up to 4% may be expected with this machine due to reductions in eddy current and ohmic losses, but applications are limited to the 5 MW (7000 HP) range (20).

The second type of DC motor or generator is the homopolar or acyclic machine which consists of a disc or drum rotating in a fixed circular magnetic field. The principle of operation is based on the Faraday disc and the design has the advantage that the loading torque is perpendicular to the stator and the armature reaction is not reflected on the stationary

field. As a result, large magnet supports are not required and the dewar
system can be relatively simple. The disc is a half-turn winding with
electrical contacts at the rim and centre. Current collection is a problem
for two reasons: one of the sliding contacts must operate at the full
peripheral speed of the disc causing severe arcing and wear, and secondly,
the current collected is very high because of the low armature voltage and
development of suitable brush material capable of supporting the current is
still in its infancy. Metal-plated carbon fibre brushes are used in the UK
and liquid metal contacts (Na, K) in an inert atmosphere are favoured in
the US and Germany. In order to increase the armature voltage, discs may
be stacked axially and connected in series or radially segmented and the
segments connected in series. In these arrangements the field magnet is
external to the disc and its position increases the overall diameter of the
motor. Greater space saving and a lower magnetic signature may be obtained
with the drum-type motor in which multiple circular solenoids are positioned
inside series-connected cylindrical rotors. Homopolar machines usually operate
at low speed and serve equally as motor or generator. Their estimated
maximum output of 200 MW is limited by brush current density (21).

Superconductive AC motors and generators are in reality a hybrid
design. The rotating superconductive field winding employs direct current
for the excitation of the AC stationary armature. A damper winding or shield
serves the dual purpose of protecting the superconducting magnet against
reactive loads due to transient electrical loads and from the alternating
field of the armature. The rotor consists of a superconducting dipole or
quadrupole magnet and the multiphase AC stator is wound with copper conductors
cooled by water, oil, hydrogen gas, etc. Normal conductors are used because
the high losses of superconductors at high AC fields renders these materials
unsuitable. Since current collection at high surface speeds is not a problem,
the rotational speed is limited only by the mechanical strength of the rotor
and dewar assembly. When used as AC generators, these machines may be coupled
directly to the turbine. Outputs as high as 3000 MVA are anticipated (20).

The refrigeration requirements of superconductive rotating
machinery increases the complexity of installations and may reduce the
reliability to a certain extent. However, the technology is well advanced
and the overall advantages of increased efficiency, relatively small size
and light weight, and, for motors, the high torque and possible low speed
operation are important factors to consider in naval and airborne applications.

Rotating superconducting machines are expected to have defence
applications in the areas of naval propulsion systems and airborne AC
electric power generation.

NAVAL APPLICATIONS

As drives for ships, superconducting motors have the advantages
of high power density, high torque and the possibility of low-speed operation.
Low rotational speed is of value in that it permits direct drive to the

propellers thereby eliminating the need for a speed-reducing gearbox with
its attendant weight and mechanical noise. In addition, electric motors
are quieter than turbines and large air ducting is not required, further
reducing fixed-location space requirements. A prime mover and generator
are necessary however, but they may be located in any part of the ship and
may also provide general electrical power for the vessel when an AC generator
is employed. The prime mover may be a diesel or a turbine engine operating
at optimum speed and coupled to a superconducting generator. The generator
may be a DC, AC or rectifier-equipped AC machine depending upon the individual
requirements and choice of propulsion motor and speed control. Cyclo-
converters (frequency changers) and variable-pitch propellers have been
proposed as speed controllers for AC drives and Ward-Leonard (field control)
circuits for DC motors. Reversing can be achieved electrically thereby
eliminating the need for reversing gears and reversible-pitch propellers.
Electrical power transmission from generator to propulsion motor is not
expected to employ superconducting cables as the refrigeration power required
is estimated to exceed the power loss due to ohmic heating in equivalent
ambient temperature conductors (22).

Since turbines are most efficient when operated at or near
maximum output, it may be desirable to have two or more prime movers plus
generators and switching network to supply the single or dual-drive motors.
In this way the power requirements for low speed and high speed cruise
situations could be satisfied. Each turbine unit could then be switched in
or out as the power demand changed (23). The use of a superconductive
electric drive system coupled with optimized turbine operation could lead to
an increase in range of up to 25% compared to an equivalent-weight, non-cross-
connected, turbine-gear propulsion system (24).

Actual on-board trials of superconductive drives designed for
naval applications have not yet been reported, although studies have been
made and models built. The DC homopolar motor appears to be the motor of
choice because it can deliver full torque at all speeds and because the
refrigeration requirements are relatively low. In the U.K. a 1 MW DC
superconducting generator and 1350 HP homopolar motor have been tested (25)
following successful operation of a 3250 HP motor in a power station (21).
In the U.S. a prototype 1000 HP shaped-field, drum-type homopolar motor has
been built at the Naval Ship R&D Centre (23,26,27), 150 kW DC generators
have been made at G.E. (28), and 3000 HP motors are under construction at
G.E. and Garrett under U.S. Navy contracts (26,29). These machines are also
considered to be prototypes for larger units to be built in the near future.

Studies of specific naval applications include designs for a
750 ton hydrofoil employing a pair of 21,000 HP DC superconductive motors
directly coupled to super-cavitating propellers to provide speeds to 50 kt.
Two 2300 HP DC motors in pods will be used for hull-borne propulsion (30).
Another advanced ship design under consideration is the 4000 ton small-water-
plane-area twin-hull (SWATH) vessel. It has been conceptually equipped with
20,000 HP superconducting motors for high-speed operations and twin 5000 HP
motors for cruise. The motor and generator efficiencies including refrigeration
for both SWATH and hydrofoil exceed 98% (27). Superconductive electric drive

systems for a destroyer with 30,000 HP per shaft driven by a gas turbine
prime mover at 4000 rpm and propeller shaft speed of 200 rpm (47), for a two-
shaft ship with 18,000 SHP per shaft (31) and for submarines (32) have also
been studied.

AIRBORNE APPLICATIONS

Practical electrical generators for use in aircraft should be
small, efficient and light weight. Conventional oil-cooled AC machines have
a specific weight of about 5 lb kVA^{-1} at 10 MVA decreasing to 0.5 lb kVA^{-1}
at 5 MVA. Generators with superconductive field windings are expected to
demonstrate a weight improvement beginning at ratings near 2 MVA and at 5 MVA
will yield 0.3 lb kVA^{-1} including refrigeration (19). This improvement is
expected to continue to increase with increasing output (33).

A 10 MVA synchronous AC generator for airborne use is under
construction at Westinghouse under USAF contract and is expected to be
completed in 1977. It is a 12,000 rpm turbine-driven machine providing 5 kV
at 400 Hz, 3 phase and weighing 426 kg. (33,34). The quadrupole rotating
field windings are housed in a rotating dewar and have been tested at design
speed and current. The USAF has also shown interest in machines with higher
output and with pulse capability (34). Superconductive AC generators in
the MW range for operation in central power stations have been constructed
and tested and work has started in England on a 1300 MW unit (35). Airborne
machines of the same rating as these generators would be lighter and
physically smaller because of their higher rotational speed. Such generators
may ultimately be used for powering airborne weapon systems requiring large
amounts of electrical energy.

Superconductive rotating machinery is not expected to become
available as off-the-shelf items, but rather will be manufactured to order,
initially following principles established from models and prototypes.
Large AC generators are under construction and will soon be proved; small
motors have been tested and scaled-up models will probably be available
before 1985 provided that financial support for development continues. The
U.S. Navy is projecting full-scale system development (40-75000 HP per
shaft) for the 1980-85 period (24).

MISCELLANEOUS APPLICATIONS

Other possible defence applications of superconductors include
use in:

(a) magnetic minesweeping by means of a towed, helicopter-
borne, high-field solenoid, with or without acoustical
sweep capability (36);

(b) detection of extremely low frequency communications
     in submarines by rotating magnetic dipole antennas (37);

(c) detection of submarines in shallow water by differential
     magnetic anomaly detection (gradiometry) employing
     series-opposition solenoids (38);

(d) stabilization of klystrons and Gunn-effect oscillators
     by superconducting microwave cavities with $Q \sim 10^9$ (39),
     and

(e) transmission of electrical power in superconducting
     cables (20).

SENSORS

INTRODUCTION

        The ability of paired electrons to tunnel through a thin
insulating layer between two superconductors without a voltage appearing
across the junction is known as the Josephson effect and has been exploited
in devices which detect extremely small magnetic fields or voltages. The
detectors operate at the quantum level and are called superconducting
quantum interference devices (SQUIDs). The junctions consist of two super-
conductors in the form of overlapping layers, a point contact or a narrow
constriction or bridge. All are termed "weak-links" because the current
flow is limited by the small dimensions imposed by the operation of the
device. The basic area of a SQUID is about 10^{-2} cm^2 and the volume of
the sensor, including substrate, connections, etc. is several cm^3. DC or
RF operation of SQUIDs is employed according to the application and when
very high sensitivity is required, the interaction with the Josephson
junction is usually modulated and the detected signal recovered in a lock-in
amplifier. When used as voltmeters, SQUIDs require a superconducting shield
to isolate them from time-varying external magnetic fields, and as detectors
of small changes in magnetic field, they require a non-magnetic dewar. Some
of the simpler SQUIDs are available as off-the-shelf items; others can be
fabricated to order. More complex systems may require developmental work.

APPLICATIONS

(a)   Of defence interest is the use of SQUIDs in magnetometers and
      gradiometers with which changes in magnetic field gradients as low
      as 2×10^{-10} Gcm^{-1} in a 1 Hz bandwidth have been reported (40).
      Advanced magnetic anomaly detection systems employing SQUIDs and,
      in some instances in combination with superconducting solenoids,
      permit the detection of submarines in shallow water where geomagnetic
      background noise is high (39).

(b)   SQUIDs have also been proposed as sensors for the U.S. extremely
      low frequency submarine communication system SANGUINE (41).
      Operating as magnetic field sensors, SQUIDs can provide fully
      omnidirectional receiving capability without the need for an
      electric field (trailing wire) sensor.

(c)   SQUIDs may be used as the sensing head for voltmeters with a
      sensitivity of 10^{-15} VHz^{-1} and as microwave and IR detectors
      with sensitivity of 10^{-15} WHz^{-1} (42).

(d)   Miscellaneous applications of SQUIDs include use in

      i)   precision readouts for gyroscopes (43);

      ii) complex logic and memory elements in ultra-fast
           computers (44);

      iii) magneto-cardiography, magneto-encephalography
           and magneto-pneumography (42,45).

CRYOGENIC REQUIREMENTS

        Provision for efficient cooling of superconductors and super-
conductive windings is essential for their successful operation. The
refrigerator must maintain the low temperature by removing heat generated
by variations in magnetic flux, local heating of superconducting wire,
movement of components and heat leaks into the system. Potting of windings
and careful design of the fluid flow, magnetic circuits, support structures,
input leads, insulation and dewars will minimize the thermal load. In
some cases a (closed-cycle) helium liquefier will be needed; in others,
a refrigerator will be sufficient if the operating temperature is above 4.2 K.

The size of existing, fixed-installation refrigerators may be approximated by the following characteristics (46):

- 1000 W input power per watt of refrigeration at 4.2 K,
- 100 kg per watt refrigeration,
- 0.15 m^3 per watt refrigeration.

Improvements in technology may be expected as the demand for greater efficiency increases. When the refrigerator is integrated with its load, its volume and weight can usually be reduced.

Sensors do not require much refrigeration power and in most cases stored liquid helium in a dewar is sufficient. Loss rates can be less than 1 ℓ per day. Alternatively, small milliwatt refrigerators may be used, but the costs are high.

CONCLUSIONS

The major areas of defence application of superconductors are considered to be naval propulsion systems, airborne AC power generation, electrical energy storage, MHD electrical power generation and magnetic anomaly detection. In all cases, an improvement in range, power output, efficiency or sensitivity may be expected. Other applications include magnetic minesweeping, ELF submarine communication and microwave frequency stabilization. The areas covered are not expected to be complete since advancing technology often brings to light new applications not previously considered, however the list presented is considered to be representative of possible defence uses of superconductors at the time of writing.

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Two basic applications of superconductivity are described. The first involves the use of Type II superconductors in magnets, motors and generators to improve efficiency and reduce weight and volume. The second relates to the use of superconducting junctions in magnetometers and gradiometers to provide instruments with very high sensitivity. Possible defence use of superconducting materials in these areas is outlined. A brief review of superconductors and their properties is also given.

KEY WORDS

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Superconducting motors

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